Attitude Determination and Attitude Control

- Placing the telescope in orbit is not the end of the story.
- It is necessary to point the telescope towards the selected targets, or to scan the selected sky area with the telescope.
- So the satellite attitude needs to be measured and controlled.

Attitude Control

- Is the control of the angular position and rotation of the spacecraft, either relative to the object that it is orbiting (Earth, Moon ..), or relative to the celestial sphere.
- The attitude control system (ACS) is composed of: Attitude Sensors, Controller, Actuators.

Estimated Attitude

- Determines the desired torques, and sends electrical commands.
- Applies the desired torques.
- Takes the measurements.

Desired Attitude

- The ACS system is composed of:
  - Attitude Sensors
  - Controller
  - Actuators

Estimated Attitude

- Estimates the current attitude.

Actual Attitude

- ACS: Gravity Gradient

Description:
Uses the change in gravity with altitude to create a torque when the principal axes are not aligned with the orbital reference frame. Long booms are usually extended to create the torque. The gravity gradient provides the restoring or stabilizing torque but does not damp the librational motion. Viscous dampers are added to dissipate the energy and damp out the librations. The gravity gradient torque can be a control torque but it can also be a disturbance torque if there are products of inertia. For example, LANDSAT had large products of inertia and the gravity gradient was the dominant disturbance torque.

Advantages:
- Simple, reliable, cheap, long lifetime.

Disadvantages:
- Poor pointing accuracy (5 deg), poor yaw control, thermal bending of boom causes oscillations, tendency to flip upside down.

(from D. Mortari)

ACS: Single Spin

- The entire spacecraft spins, which provides inertial orientation. The spinning provides gyroscopic stiffness, and stability.
- The nutation damper damps out the nutation, but precession still exists. Spinning is about the axis of maximum moment of inertia, that is usually, but not always, the orbit normal.
- Solar arrays are fixed to the body.

Advantages:
- Simple, reliable, long lifetime.

Disadvantages:
- Sensor collection is limited to scanning obtained by spin motion. High angular momentum results in poor maneuverability, i.e., reorientation of spin axis. Poor power efficiency, only half the solar cells are illuminated at any one time. Must spin about the axis of maximum moment of inertia.

(from D. Mortari)

Spinning Satellites Examples

- Spinning is used in satellites for astronomy when sky scanning is required.
- COBE, WMAP, Planck all spin at 1-10 rpm, so the telescopes (antennas) can scan the sky at a rate of deg/s.
- Complex scan patterns can be obtained by combining satellite spin and slow re-orientation maneuvers (see COBE, WMAP, Planck)
Flat spin: in the absence of perturbations the spin axis orientation remains constant with respect to the inertial frame of distant stars – Not useful for astronomy.

Using the ACS and perturbations, the spin axis orientation can be continuously reoriented away from the earth center. This is useful for full-sky surveys (COBE).

ACS: Dual Spin

Description:
The limitations of single spin satellites are partially overcome with dual spin satellites. With a dual spin satellite the payload, e.g. the antenna, is despun while the other portion of spacecraft spins to provide gyroscopic stability. Nutation is damped by nutation damper, located on either the spun or despun portion. Many of the geosynchronous communication satellites have been dual spin.

Advantages:
Despun payload allows Earth pointing payload. Can have spin about minimum moment of inertia axis. Reliable, long lifetime.

Disadvantages:
Poor power efficiency because solar cells are on spinning portion. High angular momentum results in poor maneuverability, i.e., reorientation of spin axis. Sensitive to mass imbalances.

(from D. Mortari)

ACS: Momentum Bias

Description: The momentum bias satellite is a variation of the dual spin concept that overcomes some of the problems of the dual spin. With the momentum bias spacecraft the gyroscopic stability is provided by a rapidly spinning momentum wheel rather than the bus. The payload and bus are despun or rotating at orbital rate. The momentum wheel provides control about the spin (pitch) axis and some combination of nutation damper, magnetic torquing, or propellant provide control about the yaw and roll axes. Use of propellant is avoided whenever possible. Magnetic or propellant are used for momentum damping.

Advantages: Better pointing accuracy, better power efficiency due to despun solar arrays. Still relatively cheap and not complex which means less weight than three axis systems. When the pointing requirements are not stringent, i.e., > 0.5 deg, the momentum bias ACS is usually the desired approach. The momentum bias approach with magnetic torquers is the dominant type of ACS in LEO.

Disadvantages: Usually poor yaw control. Gyroscopic stiffness results in poor maneuverability. Poorer reliability and lifetime. Due to its lower cost and complexity and relatively accurate pointing capability this has been the most popular type of ACS.

(from D. Mortari)

Dual-Spin Satellite (2/6)

A vehicle consisting of two primary components free to perform relative rotations about a common bearing axis is called a "dual-spin" vehicle, and the idea of stabilizing such a vehicle by spinning one part (the "rotor") while the other part (the "despun platform") rotates more slowly - or not at all - is called the dual-spin attitude stabilization concept.

This dual-spin configuration thus serves to create a spin stabilized satellite.
Typically a spacecraft will have several momentum wheels oriented along orthogonal axes.

To change its rotation along those axes it will increase or decrease the spin of the momentum wheels in the opposite direction. When the spacecraft achieves its desired orientation, it can then halt its rotation by braking the momentum wheels by the same amount.

Momentum wheels are usually spun by electric motors. Both spin-up and braking are controlled electronically by computer controls.

The strength of the materials of a momentum wheel establishes a speed at which the wheel would come apart, and therefore how much angular momentum it can store.

Since the momentum wheel is a small fraction of the spacecraft's total inertia, easily-measurable changes in its speed provide very precise changes in angle.

Example:

- In the CNES ACS:
  - Three magnetic ACS:
    - Three magnetic-bearing reaction wheels apply a torque on the satellite to rotate it about one of its three axes.
    - Two magnetic torquers interact with the Earth's magnetic field to generate torques and thus control the speed of rotation of the reaction wheels.
    - Thrusters complete the system.

ACS: Three Axis

Description:

All three axes are independently controlled by mass expulsion, reaction wheels (RWs) or control moment gyroscopes (CMGs). Usually RWs or CMGs are used for control and propellant (sometimes magnetic torquing) is used for momentum dumping.

Advantages:

- Pointing accuracy, maneuverability and adaptability to changing mission requirements.

Disadvantages:

- Cost, weight, complexity and lifetime.

(from D. Mortari)

ACS methods:

<table>
<thead>
<tr>
<th>Passive</th>
<th>Semi-passive</th>
<th>Active</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity gradient</td>
<td>Momentum bias with magnets</td>
<td>Propellant</td>
</tr>
<tr>
<td>Spinner with nutation damper</td>
<td>Reaction wheels with magnets for momentum dumping</td>
<td>Reaction wheels with propellant for momentum dumping</td>
</tr>
<tr>
<td>Dual spinner with nutation damper</td>
<td>CMGs with magnets for momentum dumping</td>
<td>CMGs with propellant for momentum dumping</td>
</tr>
</tbody>
</table>

(from D. Mortari)

Attitude Control Methods and their Capabilities

<table>
<thead>
<tr>
<th>Attitude Control Method</th>
<th>Pointing Capabilities</th>
<th>Maneuver Capabilities</th>
<th>Accuracy</th>
<th>Lifetime Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>True</td>
<td>True</td>
<td>Very limited</td>
<td>Constant spin</td>
</tr>
<tr>
<td>Semi-passive</td>
<td>True</td>
<td>True</td>
<td>Very limited</td>
<td>True spin</td>
</tr>
<tr>
<td>Active</td>
<td>True</td>
<td>True</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

(from D. Mortari)

Actuators

Actuators are usually broken into four classes: mass expulsion, momentum exchange, environmental and dissipative. An ACS may have actuators from any or all the classes.

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>Torque Range (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Control (RCS)</td>
<td>10^2 - 10^3</td>
</tr>
<tr>
<td>Gravity Gradient</td>
<td>10^2 - 10^3</td>
</tr>
<tr>
<td>Aeroservo</td>
<td>10^2 - 10^3</td>
</tr>
<tr>
<td>Control Moment Gyro</td>
<td>10^1 - 10^2</td>
</tr>
</tbody>
</table>

(from D. Mortari)

(from Chobotov)

From this table we see that RWs and CMGs are used when precision pointing and/or high torque is required. Satellites that perform rapid attitude maneuvers or have articulating payloads which create large disturbance torques require CMGs.
The types of sensors used for attitude determination are:
1. horizon sensors (or conical Earth scanners),
2. sun sensors,
3. star sensors,
4. magnetometers,
5. inertial reference units (Inertia Measurement Unit or attitude reference units ARU), and
6. GPS receivers.

Horizon sensors measure pitch and roll to an accuracy of about 0.1-0.5 deg. An accuracy less than 0.05 deg can be achieved by extensive calibration and accounting for the equatorial bulge. Sun and star sensors provide directions. An horizon sensor does not provide yaw information (for momentum bias systems it is not necessary to measure yaw). One wide-FOV or two narrow-FOV star sensors are needed to provide attitude. Since the star sensors cannot provide continuous attitude measurements an IMU/ARU is needed to provide the attitude between measurements. IMUs suffer from drift and biases and need frequent updates which are provided by the star sensors. Magnetometers measure Earth's magnetic. Accuracies no better than 1 deg can be obtained. The GPS receivers are used in an interferometer mode to determine attitude. Accuracies as good as 0.01 deg are expected using GPS.

Sun Sensors

Most common because they are light weight, not expensive, limited power required and because they provide an accuracy which is acceptable for most of the missions.

Sun is the principal source of energy (exemption: interplanetary spacecraft). Solar flux goes as \( 1/r^2 \).

Sun (in the Inertial Reference Frame) is evaluated by using interpolating functions (armonic series expansion) which least square fit the Sun positions recorded in the star atlas.

They are used to synchronize command with spin period, and they are used to protect star sensors.

At 1AU the sun may be considered as a point (0.267 deg.).

For GEO there is the parallax error (0.03 deg as max values).

Presence Sun Sensors

Presence sun sensors provide the sun crossing time only, or the sun presence within the sensor FOV. Used to synchronize pulsed command (spin-up, spin-down) to manoeuvre, and to turn on/off onboard experiments and instrumentation.

Analogic Sun Sensors

Based on the Snell refraction law:

\[
\frac{n \sin \vartheta}{n \sin \gamma} = \sin \Phi
\]

\( \frac{n \sin \vartheta}{n \sin \gamma} = 1 \)
Sensor #1

Sensor #2

Digital Sun Sensors

Command: sun presence

Measurement (4 parts):
1) ATA,
2) Sign bit,
3) Code bits,
4) Interpolating bits.

Digital Sun sensor

Binary and Gray code

The gain of the Gray code consists of the fact that the bit string, which represents the angle measure, changes one bit only at each digital step.

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Binary</th>
<th>Gray</th>
<th>Decimal</th>
<th>Binary</th>
<th>Gray</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>1011</td>
<td>1110</td>
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<tr>
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<td>12</td>
<td>1100</td>
<td>1010</td>
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<tr>
<td>2</td>
<td>10</td>
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<td>13</td>
<td>1101</td>
<td>1011</td>
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<tr>
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<td>10</td>
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<td>1110</td>
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</tr>
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<td>100</td>
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<td>15</td>
<td>1111</td>
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<td>6</td>
<td>110</td>
<td>101</td>
<td>17</td>
<td>10001</td>
<td>10001</td>
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<tr>
<td>7</td>
<td>111</td>
<td>100</td>
<td>18</td>
<td>10010</td>
<td>10010</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>1100</td>
<td>19</td>
<td>10011</td>
<td>10011</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td>1101</td>
<td>20</td>
<td>10100</td>
<td>11100</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>1111</td>
<td>21</td>
<td>10101</td>
<td>11111</td>
</tr>
</tbody>
</table>
Double Digital Sun Sensor

Earth horizon sensor

Best range: 14μ-16μ of CO₂ (less high altitude clouds contr.)

Relative radiance
400 (IR) and 30,000 (visible)

Earth horizon sensor

Measure two crossing times $t_1$ and $t_2$

With angular speed $\omega$, the measured angle is $\varphi = \omega(t_2 - t_1)$

Two measured angles, $\varphi_1$ and $\varphi_2$ allow to evaluate the Nadir direction.

Moon horizon sensor

Hot Moon

Hard horizon

Moon temperature range: -240 deg to +30 deg

Cold Moon

Cold horizon position

Hot horizon position

Earth/Sun sensors for spinning S/C

Meridian slit

Inclined slit

Satellite equator

Displacement angle (deg)

(i) (ii)
The Archeops Star Sensor

- Archeops was a telescope on a spinning balloon payload, designed to map a significant fraction of the CMB sky with a microwave telescope.

A fast star sensor for balloon payloads

Federico Marzi, Pietro de Bernardis, Amosco Leontychi, and Elisa Masi
Dipartimento di Scienze Fisiche, Università di Roma "Tor Vergata",
P. A. Moro 5, 00185 Roma, Italy
Alain Bensol1
Centre de Recherche sur les Étoiles Froides, CNRS, CS9249, 38042 Grenoble, Cedex, France
Domenico York2
SPITZER/3D/NGS, GTA, Sfax, Tunesia
(C) 2003 American Institute of Physics. [DOI: 10.1063/1.160261]

We developed a system to reconstruct the attitude of balloonborne experiments, where high accuracy (about 1°) and high temporal speed (up to tens of degrees per second) are required. It is based on a star sensor, and gathers together bandwidth simplicity, easy components, high resolution, and sensitivity. It is composed of an optical mirror (diameter 40 cm), an array of 40 fast and sensitive photodiodes, and low noise readout electronics. It was designed for the Archeops experiment, a balloon borne millimetric telescope whose goal is to generate high resolution maps of large regions of the sky, to study the temperature anisotropies of the cosmic background radiation.

The Archeops Star Sensor

Figure 1. Telescope frame with the fast sensor located on the central components and internal details of the photodiode box.
Optical Gyroscopes

- Terry Pearson, How a gyroscope works, February 1997, www.gyros.freeserve.co.uk) in which two light waves traveling in opposite direction in the same closed loop and generated by the same source, undergo a phase shift proportional to the rotating speed of the closed loop with respect to the inertial frame. Both laser and fiber optic gyros replaced mechanical gyros
Jupiter scans

Focal Plane

Archeops – Kiruna 2002

Star Trackers

Electronics

Optical system

Grid

Baffle

OLIMPO star camera

The camera is a QImaging Retiga Ext CCD and the PC is a 2.66 MHz Linux box. The system is provided by the ICRF of Firenze (A. Boscaglri).

A PC-104 computer is mounted inside the star camera pressure vessel. The computer runs the software that processes the CCD images.

The computer can also command the stepper motors for autofocus, and regulates the lens temperature.

The system sends the right ascension and declination of the center of the image to the right computer, which will communicate with the TM and the data storage system.

Da Nati et al. Mem. S.A. 2008
**Magnetometers**

They may be used at altitudes less than 1,000 Km, only.

(Earth magnetic field decreases with radius as $1/r^3$)

Small precision is associated with the fact that the EMF Models are not so accurate.

Biases not negligible (residuals of magnetic fields caused by onboard circuits)

**Typical GN&C Sensors (Wertz)**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Typical Performance Range</th>
<th>Wl Range</th>
<th>Power (W)</th>
<th>Some Typical Suppliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft attitude &amp; roll sensors</td>
<td>90 to 180 degrees</td>
<td>6 to 10</td>
<td>0.05 watts</td>
<td>Honeywell, Ball Bausch, Bofi, Inc.</td>
</tr>
<tr>
<td>Attitude &amp; roll sensors</td>
<td>0 to 180 degrees</td>
<td>6 to 10</td>
<td>0.05 watts</td>
<td>Honeywell, Bofi, Inc.</td>
</tr>
<tr>
<td>Magnetometers</td>
<td>0 to 180 degrees</td>
<td>6 to 10</td>
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</tr>
</tbody>
</table>